PXIE SSR1 Prototype Focusing Lens: Position of the Magnetic Axis

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Beam optics in the front end of the PXIE accelerator was thoroughly adjusted to reduce particle loss. As a result, the next requirements for the focusing system of the PXIE SSR1 cryomodule followed: the accuracy of positioning of the center of each focusing lens on the beam line in the transverse direction must be better than 0.5 mm RMS, and the precision of the angular alignment must be better than 1 mrad RMS [1]. The length of the cryomodule is ~6 m, and only optical windows at the ends of the cryostat can be used to verify position of the lenses in the beam line inside the vacuum vessel after installation on the optical bench. Having this in mind and taking into account unavoidable drift of the transverse position of the lenses related to changing temperature (from the room temperature when the beam line is assembled to the cryogenic environment during operation), pressure in the cryostat (from the atmospheric pressure to the vacuum at operation), and magnetic field (which is zero at installation), a necessity of knowing where the magnetic axis of the lens is located relative to its geometric features (which are used during the beam line assembly) becomes obvious. In the ideal case, unfortunately never existing, the two axes coincide. In reality, the relative position of the axes changes during fabrication, cooling down, and energizing [2].

In similar set of requirements for lenses of HINS accelerator [3], the required precision of alignment was set to a maximum of ±0.3 mm for positioning each end of a lens and a maximum of ±2.5 mrad of angular deviation from the beam line. To meet those requirements, it was planned to use a special cryostat with a warm bore and employ vibrating wire technique to find position of magnetic axis in each lens in the environment that closely approximates what is expected in the cryomodules. Cooling magnets to cryogenic temperature would also allow using the nominal current to feed them, resulting in a better accuracy of the measurements. Optical technique for tracking lens position inside the test cryostat and cryomodules was assumed [4].

As the use of a special cryostat became prohibitive for PXIE budget, it was decided to rely on the use of correctors embedded in each lens, which for this purpose were made stronger, and on beam-based position measurement methods [1]. As geometric features of lenses are used as reference fiducials during installation in a cryomodule, one must make sure that the magnetic axes of focusing lenses do not drift too far from the geometric axes during fabrication, especially after assembly steps that use welding.

To minimize relative movement of magnetic and geometric axes after adding the LHe vessel to the SSR1 lens cold mass by welding, which is the last operation of the magnet assembly, special measures were taken at the design stage. Welding preparation features of the bobbin and LHe vessel were introduced that would results in minimum impact on the magnetic axis position (Fig. 1). This design approach was documented in [5].

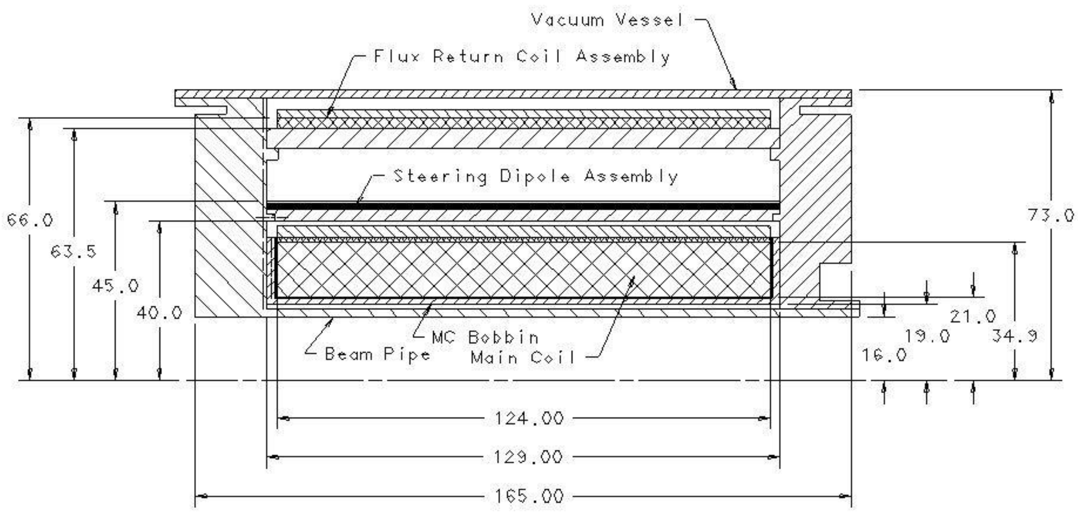

Fig. 1. Proposed approach to the lens design.

The final design of the lens was made by Cryomagnetics, Inc.; it used the approach suggested in [5] with some modifications to the bobbin design (see Fig. 2). A prototype of the lens has been fabricated at Cryomagnetics, Inc. and tested at the fabrication site and at FNAL.

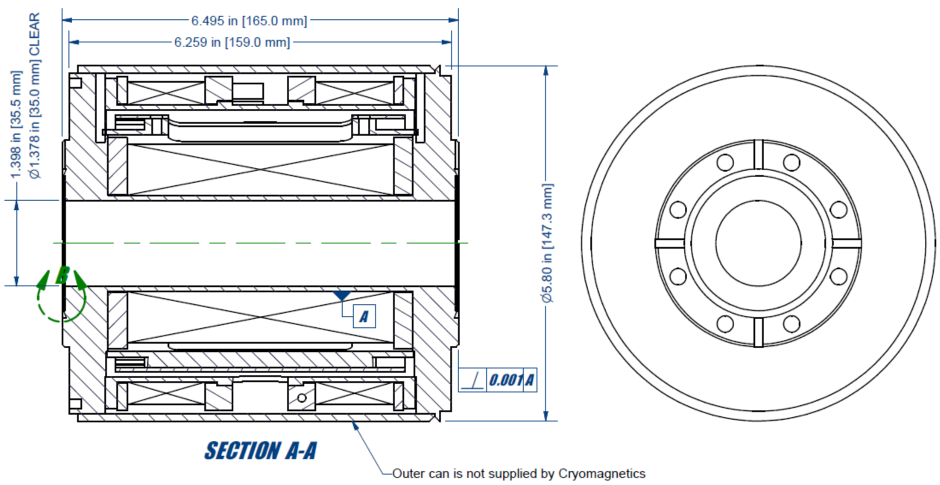

Fig. 2. PXIE SSR1 lens design by Cryomagnetics

At Cryomagnetics, the prototype was tested at 4.2 K. After lens performance test was successfully completed, position of the magnetic axis was measured using rotating Hall probe method. Precision of the measurements was not directly stated by the Cryomagnetics team; nevertheless there is certain degree of confidence that it is better than 0.1 mm RMS. The results of the measurements were fitted by a harmonic curve, and the amplitudes and the phases of this fit were used to extract the information about the deviation of the magnetic axis relative to the geometric axis of the bobbin. Fig. 3 shows the measurement data and the fit for the two ends of the coil (Z = ±64 mm).

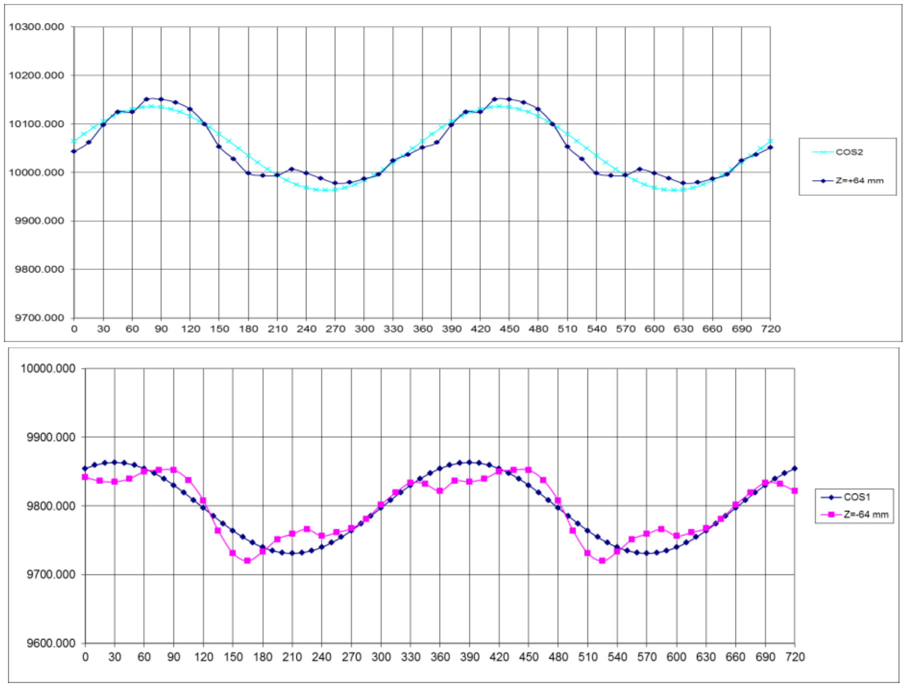

Fig. 3. Results of the axis position measurements at Cryomagnetics.

The results of these measurements are summarized in Table 1 below:

Table 1. SSR1 focusing lens magnetic axis position measured by Cryomagnetics

	ΔX [mm]	ΔY [mm]
Z = -64 mm	-0.093	-0.054
Z = +64 mm	-0.024	-0.135

The data corresponds to the next angles of the magnetic axis relative to the geometric axis:

$dX/dZ = 0.55$ mrad; $dY/dZ = 0.6$ mrad

Similar measurements were made at Cryomagnetics on the focusing lens built for the HW cryomodule of PXIE, which was also designed by Cryomagnetics. For the HW focusing lens, no measures were taken to mitigate deformation due to the welding. Table 2 provides data for the magnetic axis position for the HW focusing lens.

Table 2. HW cryomodule focusing lens magnetic axis position measured by Cryomagnetics

	ΔX [mm]	ΔY [mm]
Z = -64 mm	-0.28	+0.16
Z = +64 mm	-0.12	+0.25

The data corresponds to the next angles of the magnetic axis relative to the geometric axis:

$dX/dZ = 1.2$ mrad; $dY/dZ = 0.7$ mrad

We see greater deviations and angles for the lens made using traditional (vendor's) approach. The coordinate system used during this set of the measurements was referenced to the base flange of the lens in accordance with the marks made on its surface (Fig. 4).

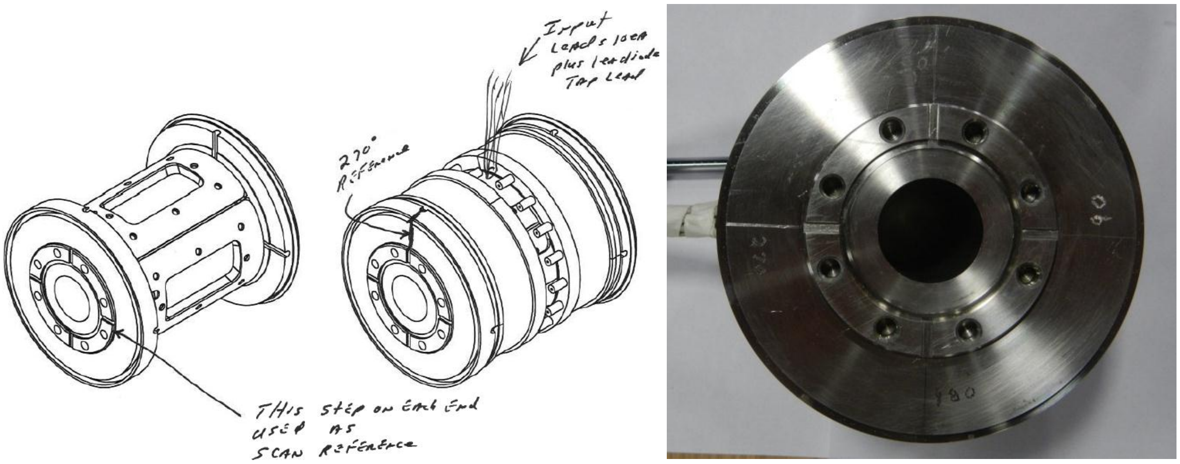

Fig. 4. Local coordinate system used by Cryomagnetics.

Measurements of relative position of the geometric and the magnetic axis were also made at Fermilab. Here the measurements were made using the vibrating wire technique at room temperature [2]. After position of stretched wire, which was set using two movable stages following an algorithm that aimed to bring the wire to an effective magnetic axis of the solenoid, was finalized, geometric features of the magnet were referenced to the stages using laser tracker.

As conditions of the measurements at Fermilab and at Cryomagnetics were quite different (different temperature, different current, and different orientation), one shouldn't expect perfect matching of the results. The main goal of the measurements at FNAL was to understand magnitude of the relative shift of the magnetic and geometric axis as a result of the welding.

Fig. 5 shows a setup used during the measurements.

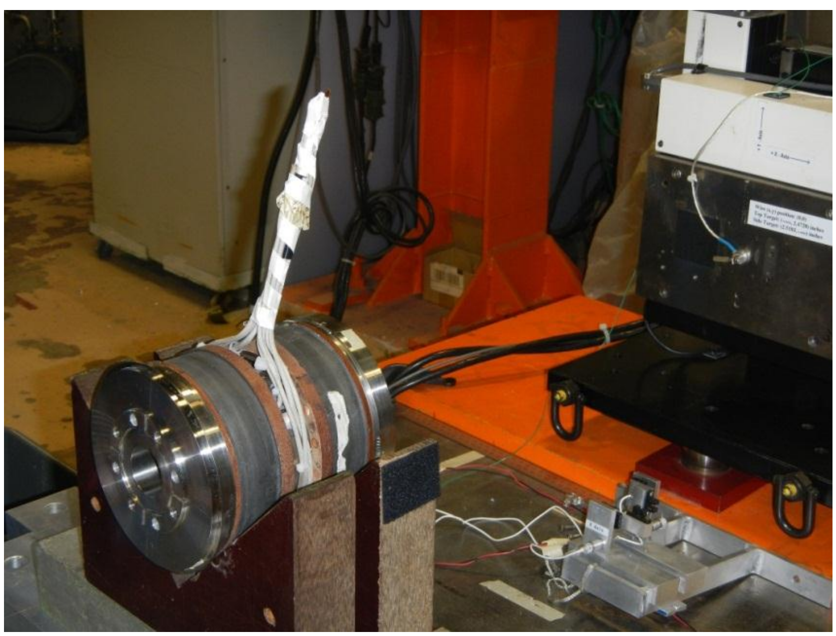

Fig. 5. SSR1 lend at the measurement stand

Reference points used during the surveillance process are shown in Fig. 6.

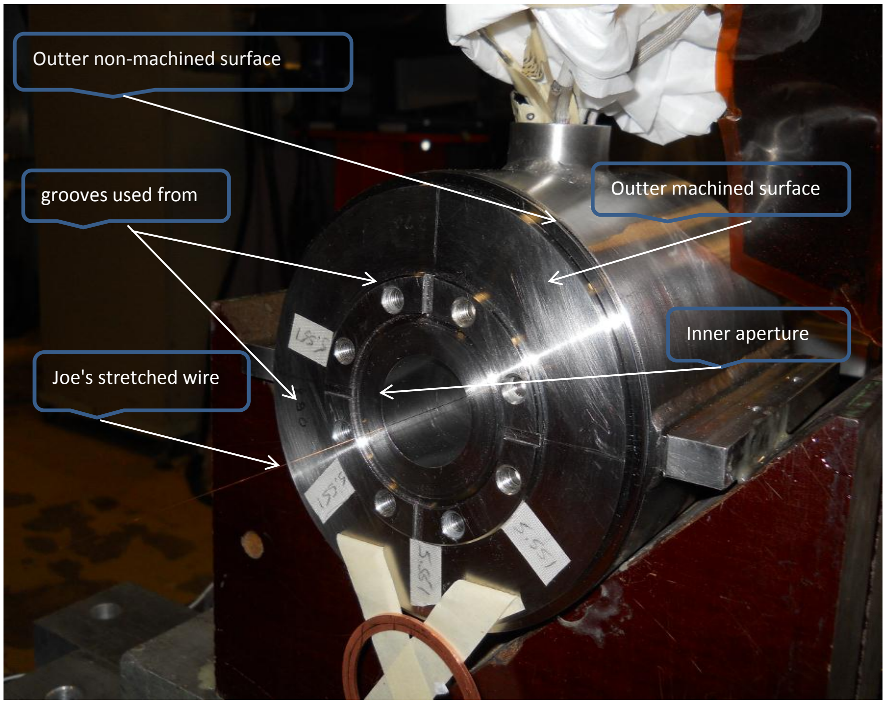

Fig. 6. Reference features used during surveillance.

System of coordinates that was used during the measurements at FNAL differed from what was used at Cryomagnetics (Fig. 7). The data set was re-worked to have it in the format used by Cryomagnetics so that the data could be compared directly.

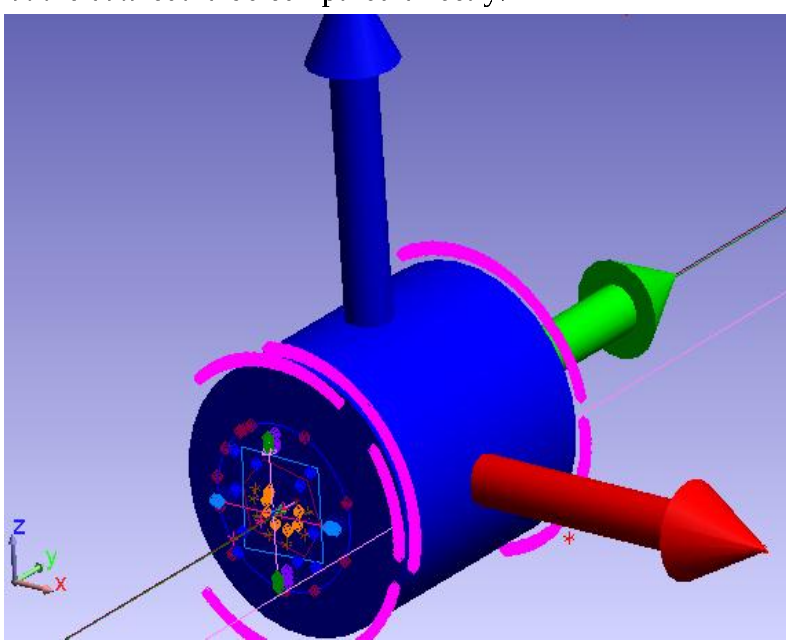

Fig. 7. Local coordinate system during surveillance process at FNAL

The process of the rework was as following:

1. For the axis along the beam pipe, the name of the Y axis (FNAL) was changed to Z (as used by Cryomagnetics);
2. The name of Z axis (FNAL format) was changed to Y (Cryomagnetics format); directions of this axis was adjusted by changing sign in the data set (in the coordinate system chosen by Cryomagnetics, the Y axis goes through the 90° azimuth in the Y = -80 mm plane to form the right coordinate system, but in the FNAL case, it goes through the 270° azimuth).
3. The data by obtained by Cryomagnetics was adjusted to the position of the end flanges by using linear interpolation.

Two tables below compare results of the measurements at FNAL before and after the welding. The data in Table 3 was taken using the inner aperture of the beam pipe; the data in the second table (Table 4) refer to the outer machined surface (Fig. 6). The expectation is that the axis position extracted using the inner bore data (Table 3) is less sensitive to the welding, than the position extracted using the measurements based on the outer surface (Table 4).

Table 3. Axis position extracted based on the inner bore survey data

	Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
Before	-82.4	0.0	+ 0.15	-0.3	-0.6
	+82.4	-0.05	+0.05		
	0	-0.025	+0.1		
After	-78.1	-0.127	+0.025	-0.3	-0.15
	78.3	-0.178	+0		
	0	-0.150	+0.012		

The data in Table 3 shows that X-position of the center changed by 0.125 mm, Y-position changed by ~0.09 mm (so, Δr = 0.15 mm), dX/dZ did not change, and dY/dZ changed by ~0.45 mrad (Δφ = 0.45 mrad).

Table 4. Axis position extracted based on the outer surface survey data

	Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
Before	-82.4	0.025	0.125	-0.15	-0.6
	+82.4	0.0	0.025		
	0	0.0125	0.075		
After	-64.31	0.178	-0.05	0	0.8
	67.84	0.178	+0.05		
	0	0.178	0		

The data in Table 4 shows that X-position of the center changed by 0.175 mm, Y-position changed by 0.075 mm (Δr=0.19 mm), dX/dZ changed by ~0.15 mrad, and dY/dZ changed by ~1.4 mrad (Δφ=1.4 mrad).

Comparing the data in the tables 3 and 4, we see that the welding does result in some deformation of the coil's bobbin. This deformation is stronger closer to the welding line, although it is noticeable everywhere.

Table 5 compares the data obtained by Cryomagnetics at 4.2 K and by Fermilab at room temperature before the LHe vessel is welded. Although these two sets of the axis position measurements were made at different temperature, current, and orientation of the coil, this comparison can give us an idea of what the level of the axis deviation can be, or how close results obtained using different techniques are.

Table 5. Axis position before welding measured by FNAL and Cryomagnegtics

	Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
FNAL	-82.4	0.0	+ 0.15	-0.3	-0.6
	+82.4	-0.05	+0.05		
	0	-0.025	+0.1		
Cryomagnetics	-82.4	-0.1	-0.043	+0.5	-0.6
	+82.4	-0.014	-0.146		
	0	-0.057	-0.095		

X-positions of the magnetic axis in the center plane of the lens (Z = 0) differ by 32 μm.
Y-positions of the magnetic axis in the center plane of the lens (Z = 0) differ by ~200 μm.
Angles of the magnetic axis relative to the geometric axis in the XZ plane differ by 0.8 mrad.
Angles of the magnetic axis relative to the geometric axis in the YZ plane did not change.

Comparing the data obtained by Cryomagnetics and FNAL, we see that uncertainty in our knowledge of the magnetic axis position and direction is ~0.15 mm and ~0.5 mrad. To reduce this uncertainty, a systematic study must be set that would use statistically significant number of the measurement cycles at both sites. Some certification of the measurement environment at both sites, including obtaining reliable information about the resolution of the measurement systems, would also help. At Fermilab, using small excitation current requires taking into account the environmental magnetic field, which was shown to be non-uniform at the location of the measurement facility. At Cryomagnetics, the measurement mechanical system is set at room temperature and used at 4 K, and no data exists on possible deformation and accuracy.

Nevertheless, having in mind the required alignment precision, results obtained using both methods show that the inner bore of the lenses can be used during lens installation in the cryomodule as a reference feature. The method used by Cryomagnetics, although possibly having higher systematic error, definitely has better sensitivity as the measurements are made at the nominal current and temperature.

For the production lenses, only the measurements made by Cryomagnetics will be used.

References:

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